Instituto Nacional

de Ciências e Tecnologia de Timor Leste

Relatório de
Investigação Cientifica INCT 2024

GEOSCIENCE INVESTIGATION ON NATIONAL ROAD FAILURE AT LUGATOI AREA, VIQUEQUE MUNICIPALITY, TIMOR LESTE

Investigador Responsavel
Moisés Soares

Dili, Novembro 2024

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Área de Conhecimento: Geociencia
Estudo Elaborado por:

Investogador Responsavel: *Moisés Soares*

Investogador 1*: Antonio de Jesus Lira*

Investogador 2*: Flavio Maria da Graca Amaral*

Investogador 3: *Filomena de Jesus Alves*

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Declaração

Nome do Investigador Responsavel : Moisés Soares

Endereco Electronico : Bidau Massau, Dili

Telefone: +670 77929227

Numero de Bilhete Identidade: 06030320079092856

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Assinatura do Investigador Responsável...

Abstract

Has been carried out multidisciplinary methods in investigating road failure at Lugatoi area. The road failure has been conducted frequent maintenance within three years. Drone mapping shows discontinuity shape of morphology reflect the structural geology. Lithological, the road failure is located precisely on clay material which is product diapiric mélange. Various size of alien block of rock embedded into the clay observed along the river, this rare in landslide location. The mélange possible has relationship to the strike-slip fault that linear to discontinuity shape. Topographically, the road failure is located on a slope has values 45-50 degree. Vertical Electrical Sounding inversion show at depth 0.5 m to 30 has lowest resistivity value. This well correlated to geology observation, very wet clay and weathered siliceous argillite. Laboratory analysis reveal the result agreeable to geological condition. Further geophysical survey recommended to obtain detail subsurface information prior to maintenance construction. Avoid high slope for alternative road due to high plasticity on a high slope prone to road failures.

Key words: *VES, landslide, road failure, Geotech, geology, drone.*

Resumo

Foram utilizados métodos multidisciplinares para investigar a falha de estrada na área de Lugatoi. A falha da estrada passou por manutenção frequente nos últimos três anos. O mapeamento por drones mostra a forma de descontinuidade da morfologia que reflete a geologia estrutural. Litologicamente, a falha da estrada está localizada precisamente em material argiloso, que é produto do mélange diapírico. Diversos tamanhos de blocos alienígenas de rocha embutidos na argila foram observados ao longo do rio, algo raro em locais de deslizamento de terra. O mélange possivelmente está relacionado à falha que é linear à forma de descontinuidade. Topograficamente, a falha da estrada está localizada em uma encosta com valores de 45-50 graus. A inversão de Sondagem Elétrica Vertical mostra, a uma profundidade de 0,5 m a 30 m, os menores valores de resistividade. Isso está bem correlacionado com a observação geológica: argila muito úmida e argilito silicioso intemperizado. A análise laboratorial revela resultados concordantes com a condição geológica. Recomenda-se uma pesquisa geofísica adicional para obter informações detalhadas do subsolo antes da construção de manutenção. Evite encostas íngremes para estradas alternativas devido à alta plasticidade, que as torna propensas a falhas.

Palavras-chave: *Sondagem Elétrica Vertical, deslizamento de terra, falha de estrada, Geotecnia, geologia, drone.*

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1. INTRODUCTION

1.1. Background

Timor-Leste is hilly terrain; it is around 70% and the rest are the flat area. This hilly terrain as the result of collision between Australian Margin Continent and Banda-Arc. Complexity of geological history has potential to be geotechnically issues in entire of country. One of the most product prominent in Timor-Leste is mélange. This product is challenging in an infrastructure construction if without proper investigation methodology.

Figure 1. Road damage caused vehicle accident even lose life in February 2024 (Source: FB Santos R.)

In Timor-Leste the multidisciplinary study for a construction have never been carried out systematically. A recent multidisciplinary between geology and geophysics in studying highway damage was conducted by Soares *et al* (2022). However, this study did not include proper Geotech data analysis. Therefore, multidisciplinary highly recommended in preconstruction stage in order to understand the existing potential hazard. The essential purpose of multidisciplinary studies may have comprehensive knowledge related to geometry, hydrology, soil properties and existing kinematic of landslide itself (Rezaei *et al*. 2018).

Integration of systematic engineering geology practice is fundamental in facilitating engineering design (GEO,2007). The findings from prior research should be recorded in the form of journal articles, conference proceedings, and technical reports to facilitate future studies. Besides, major geotechnical issues in Timor-Leste that effecting the damage of infrastructure is frequently in mélange area. Mélange is a product of tectonic complex that has the chaotic rock (Festa *et al*, 2022). For instance, Suai highway damage (Soares *et al* 2022), road damage in Bobonaro area (Martins *et al*, 2020), veteran grave damage in Quelecai (IPG,2022), bridge damage in Bualale (IPG, 2022), road damage in Maliana (Cornelio *et al*, 2023). Consequently, infrastructure construction requires systematic study on geological process and their spatial distribution such as structural geology, weathering, geomorphology, and hydrogeology (GEO,2007).

In the last five years, the maintenance of the road has been conducted more than three times due to the road damage. In Timor-Leste obviously shows absence of geoscience involvement in various megaprojects. For instance, some section of Suai Highway coincides cross over the mud diapiric zone and highly deformed of bedding with dipping to the highway (Soares *et al*, 2022). This because, the megaproject was only responsible by Civil engineering, where they carried out Cone Penetration Testing (CPT) and standard penetration Testing (SPT) only to conduct feasibility study.

This because in government institution which is review the proposal and responsible of the megaproject lack of involvement of geologist and geophysicist. Normally, the contractor submits the proposal of the feasibility study (FS) that should include the geology and geophysics survey. All method does not applicable in a specific site in order to decide the suitable methods requires the involvement of geology and geophysics studies in this early stage. The geological information is crucial to locate the Geotech borehole geophysical survey lines. Combination of these methods provide significant insight in proposing the construction method that should fit to the geological subsurface condition. Therefore, in this study we attempt to combine several geoscience methods in assessing the Lugatoi road damage. Drone survey, geology, geophysics, and geotechnical investigation were applied in this research project.

1.2. Objective

The primary objective of this study as follows;

a. Identify the geological hazard along the road damage at Lugatoi area specially in landslide zone
b. Applied geology and geophysics method to reveal the surface and subsurface geological condition respectively
c. Applied geotechnical study to understand the material condition in the landslide zone and nearby area.

2. STUDY AREA

Administratively, Lugatoi is located in Caraubalo village, Viqueque Municipality. The landslide that damaged the main road access to capital of the country precisely in coordinate -8.864350° and 126.362012°. The main road is situated in the western bank of Cuha River and parallel to the river (see Figure 2).

The area is well known by local people even national due to the road damage that occurred every year. In term of accessibility, it is a unique national primary route of land transportation from Viqueque Municipality to the capital of the country and vice versa. Therefore, disturbance of the road may possibly slow down the local economic movement even transportation accident.

Figure 2.Location of study area (google map,2024)

3. BRIEF GEOLOGYCAL SETTING OF TIMOR-LESTE

Timor-Leste is located in the southeast of Indonesia, and northern of Australia. Timor is the largest island of the non-volcanic Outer Banda Arc (Audley-Charles, 1968). Timor-Leste located in the site of an active arc-continent collision between the Banda Arc and the Australian continental margin (Masson *et al*, 1991). The Banda arc and the Australian continental margin form a transition zone from subduction to arc-continent collision. The subduction began in the Timor Island in the late Miocene (Audley-Charles, 1968; Cox, 2009). The collision began in central Timor and continue migrates to the south at about 110 km/Ma (Harris, 1991).

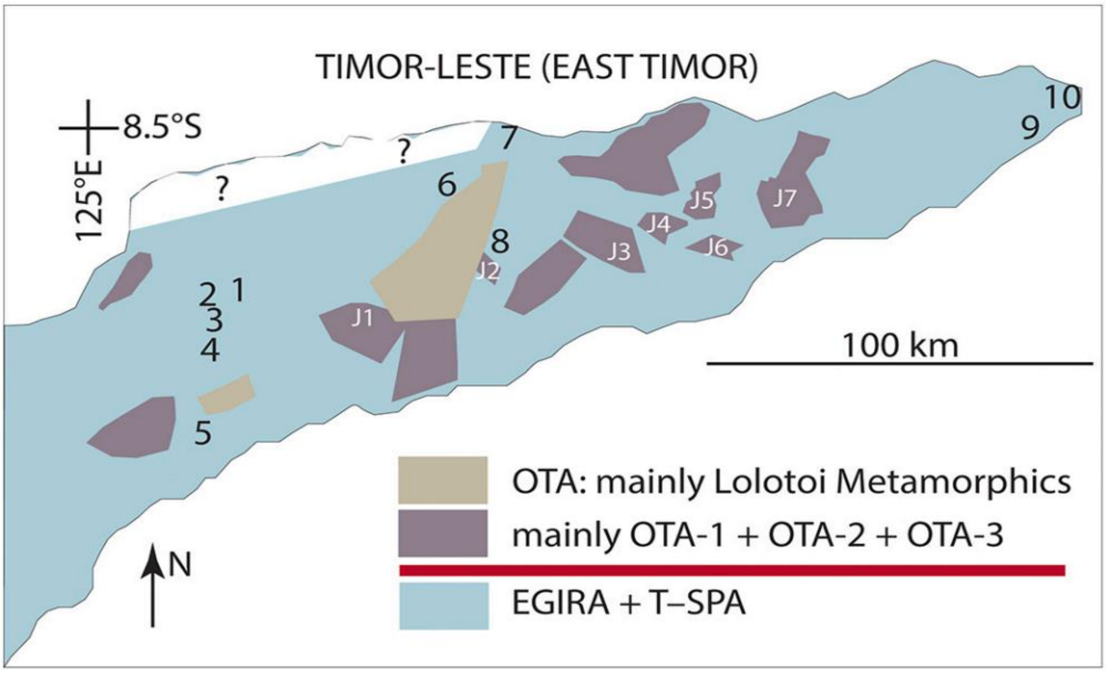

Figure 3.Regional tectonostratigraphic map of Timor-Leste (Haig et al,2021a)

There are three main types of deformation in transition from subduction to collision such as; pre-collisional, transitional and collisional. The pre-collisions stage of Timor began at 5-8 Ma, the result of the pre-collision formed Sunda arc. The transition phase began collision in Timor Leste at 5-3 Ma, nowadays this event still active in Sumba, Savu and Rote. Another represents of this phase developed back thrust system and marked by initial uplift of arc and forearc region. The collision phase started in Timor-Leste about > 3 Ma.

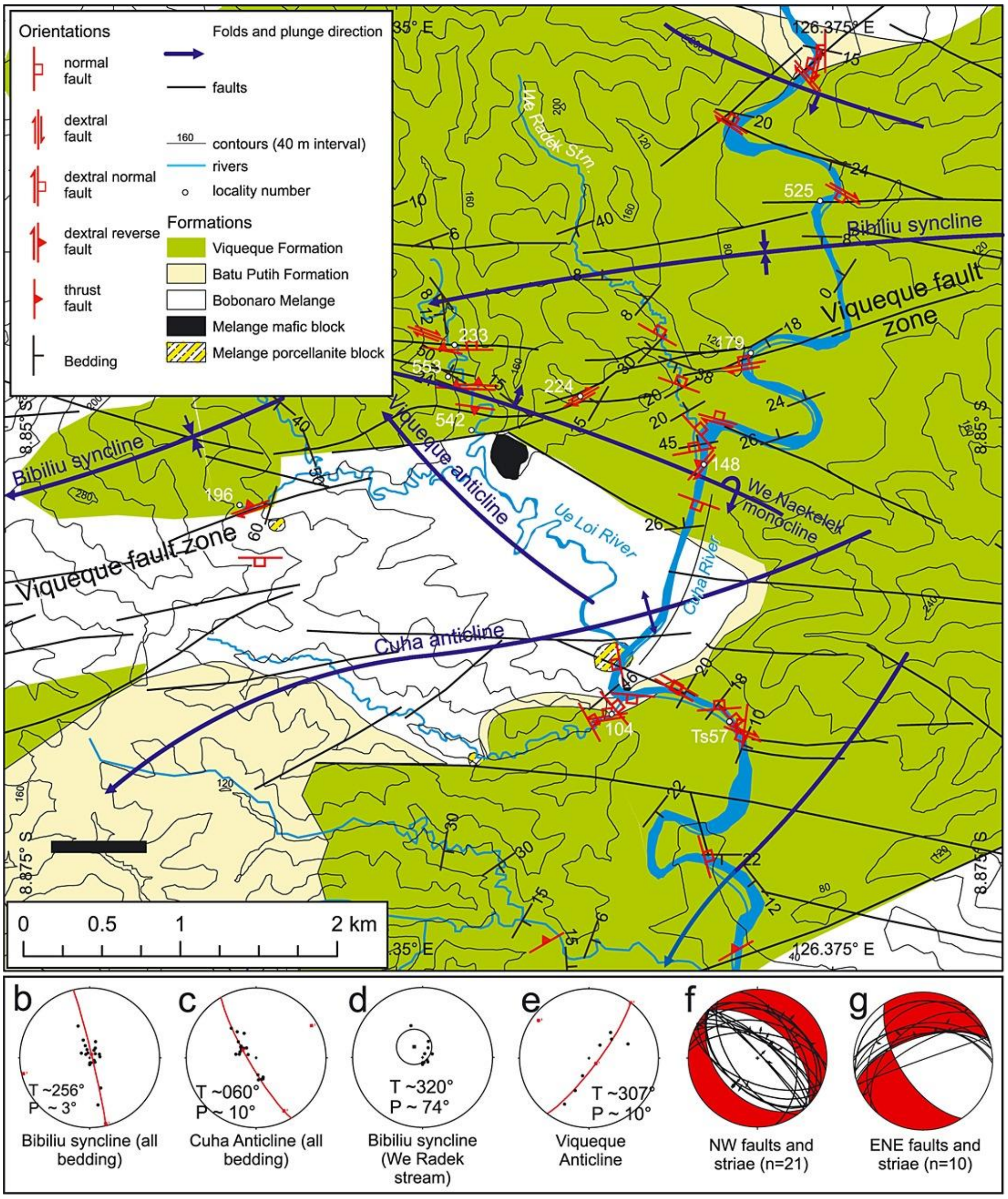

Figure 4.Geology map of Viqueque area (Duffy et al, 2013)

With updated tectonostratigraphic association of (Haig *et al*, 2021a), classified into four categories: the East Gondwana Interior Rift Association (EGIRA), the Timor Scott Plateau Association (T-SPA), the Overthrust Terrain Association (OTA) and the Synorogenic Association (see Figure 4). The EGIRA is pre-breakup intra-cratonic basin deposits from Late Carboniferous to middle-Jurassic ages. The T-SPA post-breakup veneer of mainly pelagite sediments on the EGIRA with the geological ages from late Jurassic to late Miocene. The OTA is confined to terrane blocks where amalgamated prior to collide with the Australian continental margin, then thrusted onto the EGIRA. The geological ages of the terrane are ranged from Early Jurassic to Middle Eocene. Synorogenic association is the deposition after collision in the late Miocene, and the deposition continues to the aged from late Miocene to present day.

Structurally, sedimentary layers from the EGIRA are composed of limestone and shales have been undergone thrust stack, but the carbonate pelagites of the T-SPA involved thin thrust slice. While the OTA intensively and irregularly faulted and folded. Following recent strike slip faults, they indicate the last stage of the orogen in Timor-Leste and they formed as the product of oblique collision between the Australian passive margin and the Banda Arc (Benincasa, 2015).

Locally, Duffy *et al* (2013) mapped the study area is covered by the block mélange. The mélange zone was bunded by the Synorogenic rocks in Pliocene (Batu Putih and Viqueque Formation) in south and curves eastward to north-east. Stratigraphically, the Synorogenic rock unconformably overlying on the various oldest rocks. In the study area we suppose the Synorogenic overlies on Noni formation. The following work of Haig and Bandini (2013) examine the block is Jurassic age called Noni Formation. Furthermore, the up to dated tectonostratigraphic study of Nano *et al* (2023) suggested the Noni formation considering of Overthrust Ocean Basin Association (OOBA).

Structurally the Figure 4 demonstrates the faults trending to the east-west and northwest-southeast. Precisely in the study area a structure overprinted over the block of mélange later know as Noni Formation. Moreover, the regional folding marked on the map and their fold axis mostly to the northeast-southwest. Butakoff (1969) suggest the study area is a piling of diapiric melange. This possible the material of diapiric melange origin from the rock of EGIRA. The major structure occurred on the overthrust rock on to the EGIRA, Noni Formation, acts a main pathway for the overpressure material from subsurface. This similar what reported by the Boavida *et al* (2023) in Raisut area, 10 Km south of Lugatoi. The difference is the overthrust rock are hidden beneath the surface. Road construction was constructed on the top of this diapiric melange zone since Portugues occupation. Due to the hazard level, the Timor Portugues government marked this area as '*area perigo'* in English is danger zone.

4. METHODOLOGY AND INSTRUMENTS

In investigating road failure maintenance conducting comprehensive geology, geophysics and geotechnical study are highly recommended. Integration of multidisciplinary provide critical data about the significant subsurface condition, material properties and potential geohazards. Due to the information has the crucial influence the planning and execution of maintenance activities.

Figure 5.Equipment that used in this investigation

Therefore, investing the proper studies prior to maintenance can lead to significant cost saving, avoid frequent repairs in short time/longevity of road. In addition, drone mapping applied because it provides high-resolution imagery and digital terrain models quickly and cost-effectively over large areas.

4.1. Drone Mapping

Recently, drone mapping has become a valuable tool in geological hazard mapping. This is because it provides high-resolution imagery and digital terrain models quickly and cost-effectively over large areas. This efficiency reduces the time and cost associated with traditional surveying methods. Utilizing high-resolution imagery enables detailed, critical understanding of the dynamics in landslide-prone areas. Additionally, it provides valuable data for monitoring and assessing landslide risks in the future at the same location.

Figure 6.Drone imagery looking from south

The technology captures detailed images useful for identifying geological features, especially in areas difficult for humans to access. Drones can create detailed maps of rock formations, faults, and related geological features. In studying geological hazards, the dimensions and orientations of faults are vital for identifying structures that govern the hazards. By integrating drone technology into structural geology, researchers can significantly enhance the accuracy, efficiency, and depth of their investigations.

In this research the DJ1 drone was used to capture the imagery and the digital terrain model in the study area. Visualization of slope map and others related map used Global Mapper software. The discussion and interpretation of DTM and imagery will be found in section result and discussion of this report.

4.2. Detail Geological Mapping

Geological mapping is a critical tool in understanding and mitigating road failures. This provides information about the rock formation, rock stratigraphy, structural geology features, and level of weathering of the rocks itself. The data are vital in assessing the potential geological hazard due to they can impact the road stability. The existing lithologies has various properties due to endogenic and exogenic process such their hardness, permeability and weathering characteristic. Where, the degree of weathering can affect the strength and durability. Moreover, sequence of rock formation and geological structures that may cause ground instability.

Figure 7.Observing a normal fault

By identifying and analysing existing geological features such as rock types, faults, and soil composition (see Figure 7 and 8). For instance, the presence of clay-rich soils can lead to swelling and shrinkage, which weakens the road foundation. Therefore, prior to road failure maintenance geological information is crucial for understanding existing geological hazards, especially landslides in Lugatoi area. Similarly, faults and fractures in the bedrock can create zones of weakness that compromise the road's structural integrity. This information invaluable in selecting suitable construction method in order to secure the long-term sustainability of road. In other side, geological data combine to other related data to select the effective maintenance strategies.

Observing an obvious normal fault occurred on Batu Putih Formation (above), measuring the dip direction of Batu Putih Formation in Cuha River (below). Preliminary interpretations from drone mapping provide essential information for conducting more detailed geological investigations. For example, the discontinuity of topography can reflect geological structures, and high elevation can indicate hard rock formations.

Structural geology measurements and outcrop observations were conducted in the landslide area and its surroundings. Specifically, in the landslide zone, the surface was excavated to expose the original material. Various fractures and structural geological features overprinted on the siliceous argillite were measured down to the river. A Brunton geological compass was used to measure the strike and dip of bedding, and the types of faults were observed.

Figure 8.Measure a bedding of rock

Moreover, geological information is an essential parameter for designing vertical electrical sounding (VES) points and borehole rock and soil sampling. Without proper geological information, rock and soil samples may not represent the existing rocks in the study area accurately. On the other hand, ensuring that VES points cover the entire area with different geological conditions provides a comprehensive understanding of the subsurface. Obtained all geological information input into ArcGIS software to generate the various geological maps. In addition, the 3D geological model view used CorelDraw software.

Figure 9.Block of volcanic rock in the bank of Cuha River.

4.3. Geophysical Survey

In Timor-Leste geophysics survey is very limited due to various factors such as lack of understanding importance of geophysics in infrastructure construction, availability devices, and human resources. First near-surface geophysical investigation for infrastructure failure in Timor-Leste was conducted by Soares *et al*, 2022. Their result indicated block of hard sedimentary rock embedded into clay in diapiric mélange zone well figured out. Moreover, saturated layer of the clay which is has slope as the main contribution to highway damage.

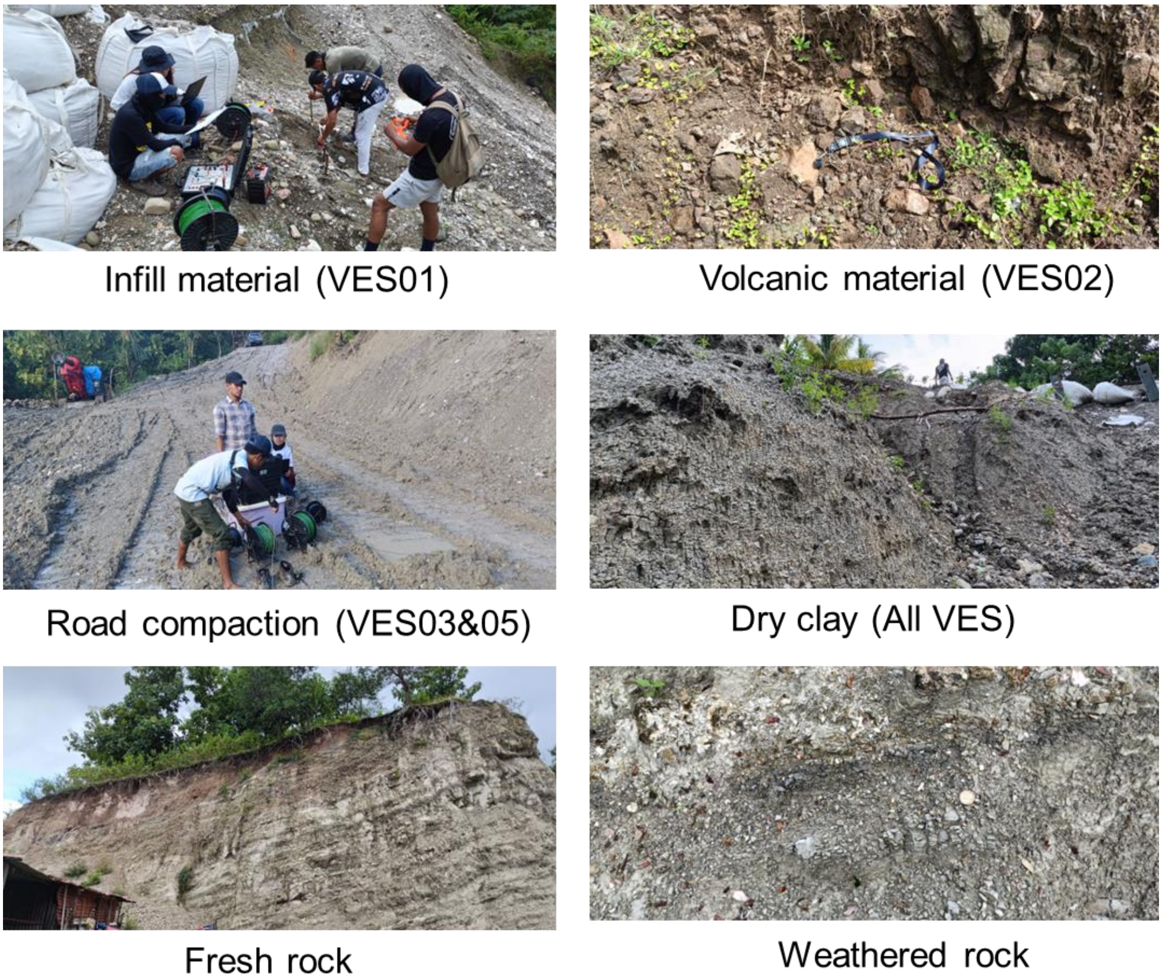

Figure 10.Surface condition of VES site points

Vertical Electrical Sounding (VES) is a non-destructive method for investigating the subsurface without disturbing the physical structures of materials (Devi *et al*., 2017). VES data provides information about material distribution beneath the surface based on the electrical properties of rocks. Rock resistivity varies depending on the properties of the rocks themselves, such as porosity and fluid content (water). Igneous and metamorphic rocks typically have high resistivity values. The resistivity of these rocks greatly depends on the degree of fracturing and the percentage of fractures filled with groundwater (Loke, 2004). Unconsolidated sedimentary materials usually show low resistivity variations, indicating higher water content or intergranular aquifers. Groundwater resistivity values generally range from 10 to 100 Ω·m.

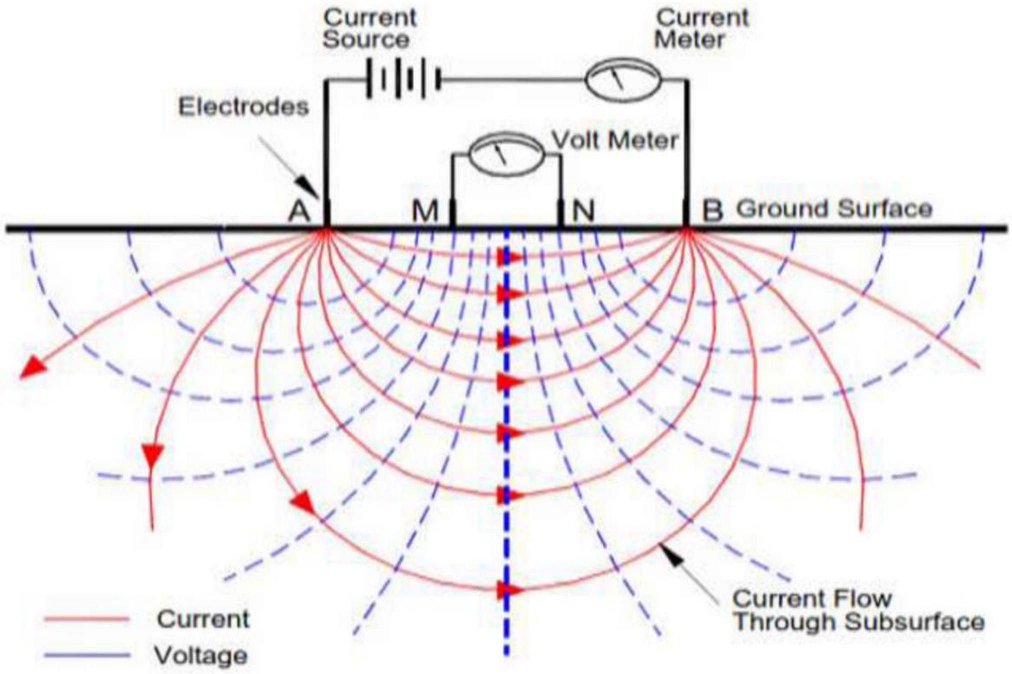

Figure 11.Illustration of Schlumberger array

The Schlumberger configuration was used to collect the VES data (Figure 11). In this method, the outer electrode spacing is kept large compared to the inner electrodes. Current is injected through the current electrode, and voltage is measured through the potential electrode. The apparent resistivity is then calculated from the measured current and voltage using the earth's properties. The resistivity value is most influenced by the geometry factor of the array. Therefore, before obtaining resistivity, the geometry factor (K) of the Schlumberger configuration must be calculated.

During data acquisition, quality control can be carried out directly in the field. The data is then input into a computer for processing prior to the interpretation stage. Data processing is done using Excel software. The inversion process in IP2Win software provides an error value that indicates the magnitude of the model error.

Finally, the interpretation stage converts geophysical anomalies into a geological model. Combining geological information with resistivity anomalies can generate an understanding of the subsurface conditions. The obtained model is useful for predicting the spatial distribution of materials that could potentially cause landslides, such as those that led to road failure in the Lugatoi area.

4.4. Geotechnical Investigation

Geotechnical investigation in this study is collecting the soil and rock samples. The sample collection is a crucial step in understanding the physical and mechanical properties of soil and rock in the area occurred failure road. This information useful in assessing the suitability of ground condition for road construction and could use to reveal the existing potential geohazards.

Figure 12.Hand auger (left), pipe tube for collecting the undisturbed sample

This meticulous procedure involves careful planning, proper sampling techniques, and stringent handling protocols to preserve the integrity of the soil samples from collection to analysis. Both disturbed and disturbed samples were collected, each serving different purpose in laboratory analysis. The disturbed samples were collected using hand auger while undisturbed samples using pipe tube (see Figure 12). The pipe tube may maintain the soil natural structure of samples. The 10 cm and 30 cm high pipe tube was used to collect the undisturbed soil. Disturbed samples used to test the soil and rock properties such as moisture content, atterberg limit, and specific gravity. While, the undisturbed samples used to test the shear strength. The shear strength provides the information of material's shear stress which is critical for slope stability and foundation support of road construction. Finally, all the samples conducted the laboratory analysis at Civil Engineering Laboratory of National University of Timor Loro Sae'e Hera Dili Timor-Leste.

Figure 13.Location soil sampling. BH1 and BH2 upper left to right, and BH3 and BH4 lower left to right.

Geology and preliminary geophysical interpretation guide to select the location of Geotech sample collection. Clearing surface of the sample point from debris, or loose layer to avoid contamination. Labelling the sample using permanent marker and documentation about sample condition. This can be easy in accurate tracing back to each sample information and prevent mix-ups and contamination of samples. In order to maintain the quality of samples required a proper sample box. This can protect the samples from external contamination, maintain samples' natural condition, and easy in organizing the samples. The samples wrapping using plastic wrap to avoid contamination then store in the sample box (see Figure 14). This leads to accurate and reliable geotechnical analysis, providing valuable data for engineering and construction projects.

Figure 14.Sample of Geotech investigation

5. RESULT AND DISCUSSION

In this report the results of each method will be discuss separately. Integration of obtain result would be used to define the main purpose of the study. In this section composed of drone mapping, detail geological observation, geological hazard, VES of geophysics and Geotech describes in separate section.

5.1. Drone Mapping

Drones can cover large areas quickly and provide high-quality data. High-resolution aero photo with a drone is a crucial part for assessment of different types of geological hazards, combined with detailed DTM (Digital Terrain Model) which allowed a detailed evaluation of the slope morphological features of Lugatoi landslide. Combination of aerial imagery and DTM may help in identifying cracks and flow accumulation of landslide.

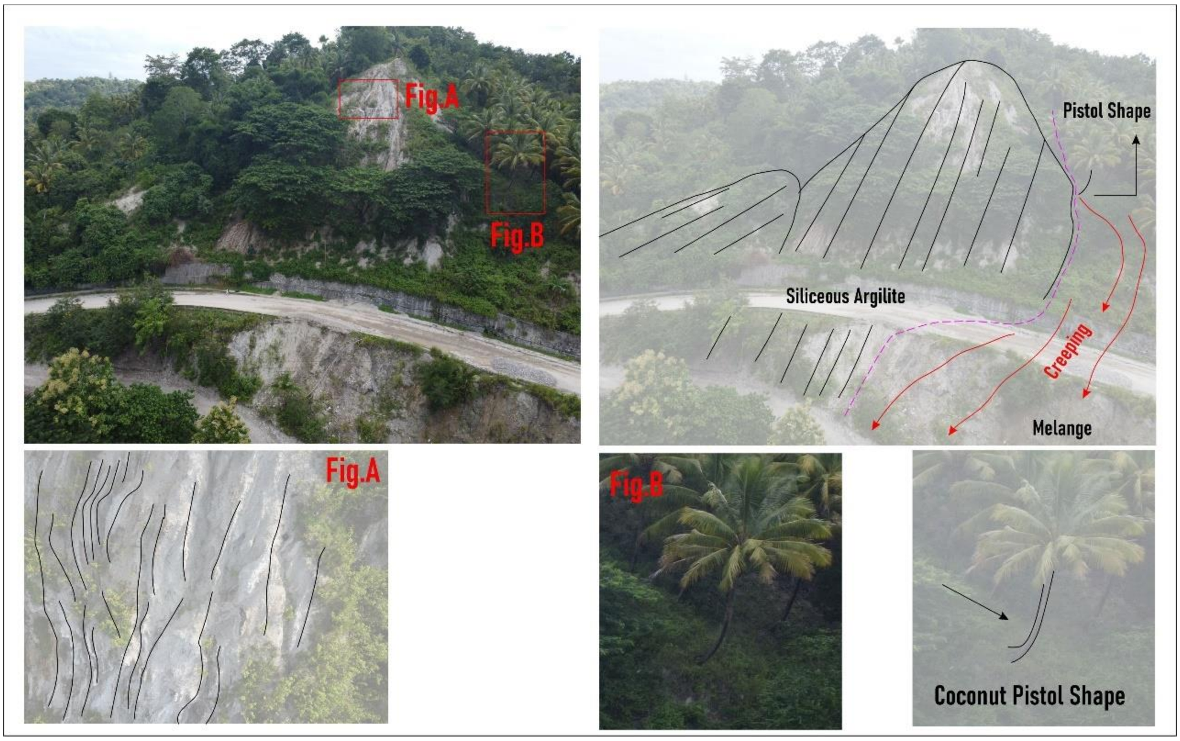

Figure 15.Aerial imagery and DTM data allowing in characterizing the landslide at Lugatoi

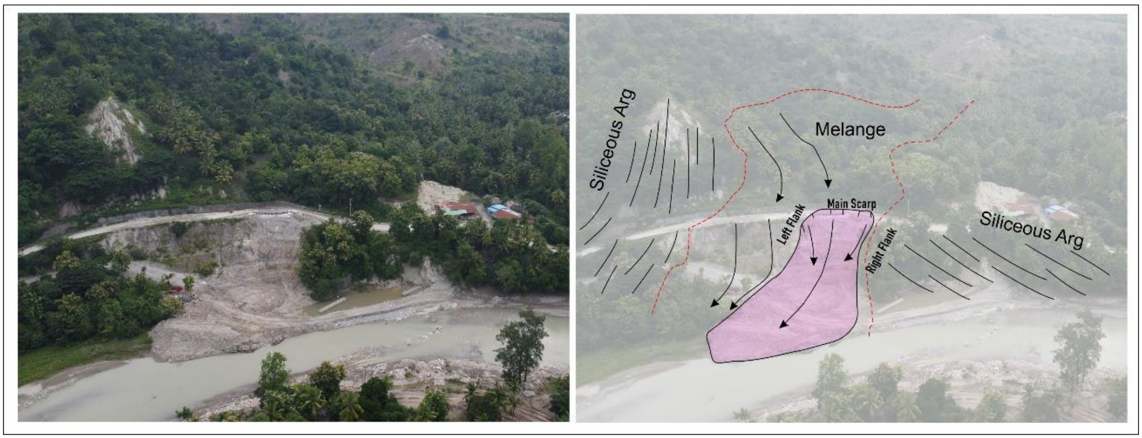

Figure 16.Interpretation of landslide according to aero photo

The aerial imagery and DTM of drone provide preliminary information prior to detailed field investigation (see Figure 15). Drones creates detailed maps and 3D models view of landslide-prone areas as display in Figure 16. These models help in understanding the topography and identifying potential risk zones. This allowing assessing the dynamics of landslides and predicting future movements. Drones can access remote or dangerous areas that are difficult for humans to reach. This makes them invaluable for surveying landslides in rugged terrains. Before proceeding to the field for ground checks, topography interpretation was conducted. This allows to understand the shape of topography that could related to the local geological structures (see Figure 16).

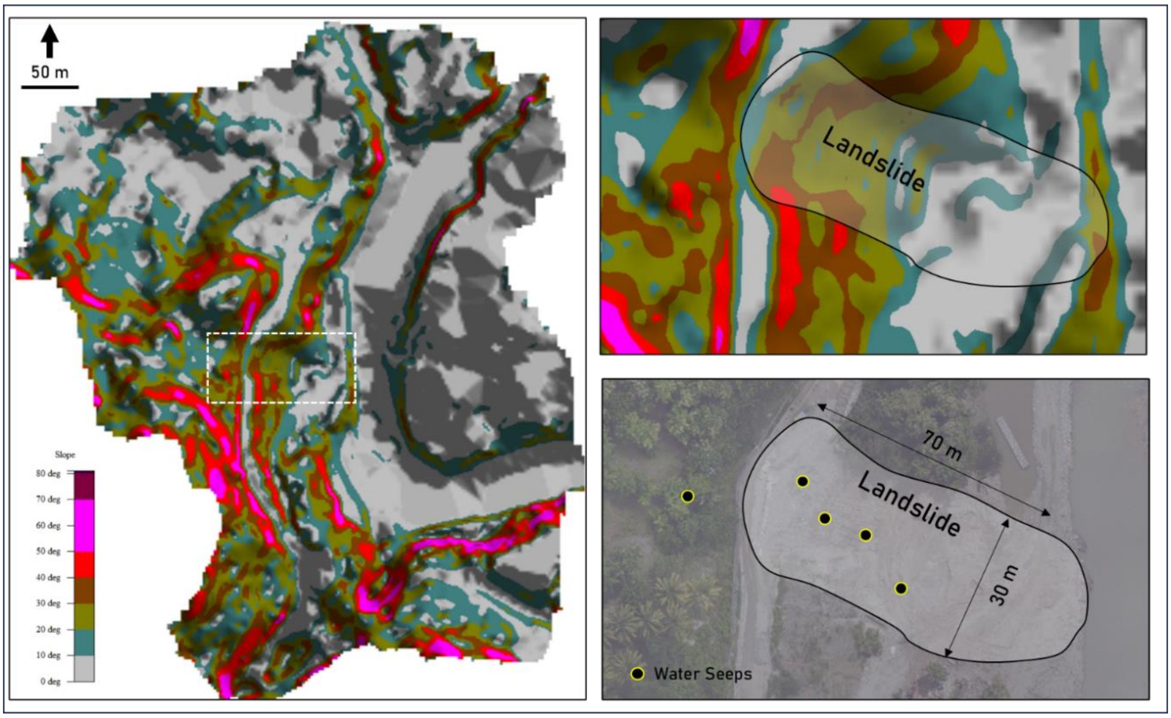

Figure 17.Slope map of study area

The Digital Terrain Model (DTM) obtained from drone imagery is useful for understanding the geomorphic changes that occur before and after a landslide. This is clearly observed on the slope map in Figure 17. Prior to the landslide and surface excavation, the slope was approximately between 40 and 50 degrees, as seen on the left and right flanks of the landslide, where the terrain is steep. Due to the unstable slope in the area, which is mostly covered by clay, the material moved downslope, altering the landscape and consequently causing road failure. The length of landslide extends from the main scarp precisely on the road failure down to the river is around 70 m. Its width approximately 30 m from the left to right flank of landslide. Further to the high elevation, around 35 m a small landslide occurred with length and width 10 m and 7 m respectively (see Figure 17).

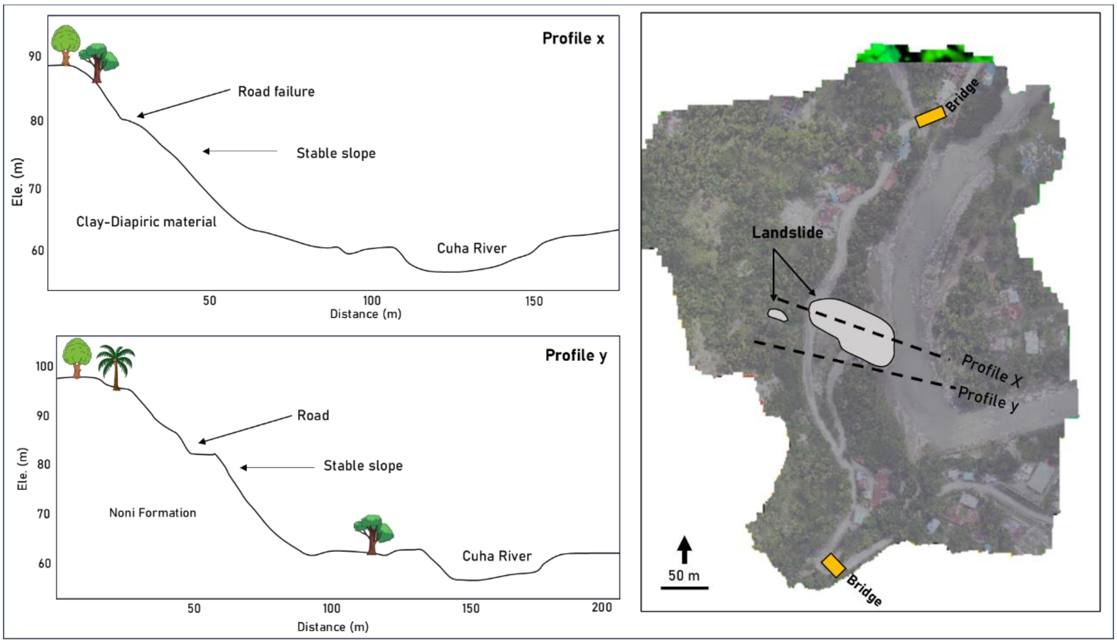

Figure 18.Elevation profiles of stable and unstable slope

Figure 18 shows two different elevation profiles. Profile X indicates the slope of the geomorphology along the landslide, while Profile Y represents the area beyond the landslide zone. Both profiles display differences in terrain shape. Initially, they had similar features with slopes around 40 to 50 degrees. However, the landslide altered the surface terrain along the landslide zone. The elevation at the point of road failure is approximately 85 meters above sea level. The landslide occurred on the area mostly covered by the clay. While the area which occupied by the siliceous argillite does not interrupt by the landslide.

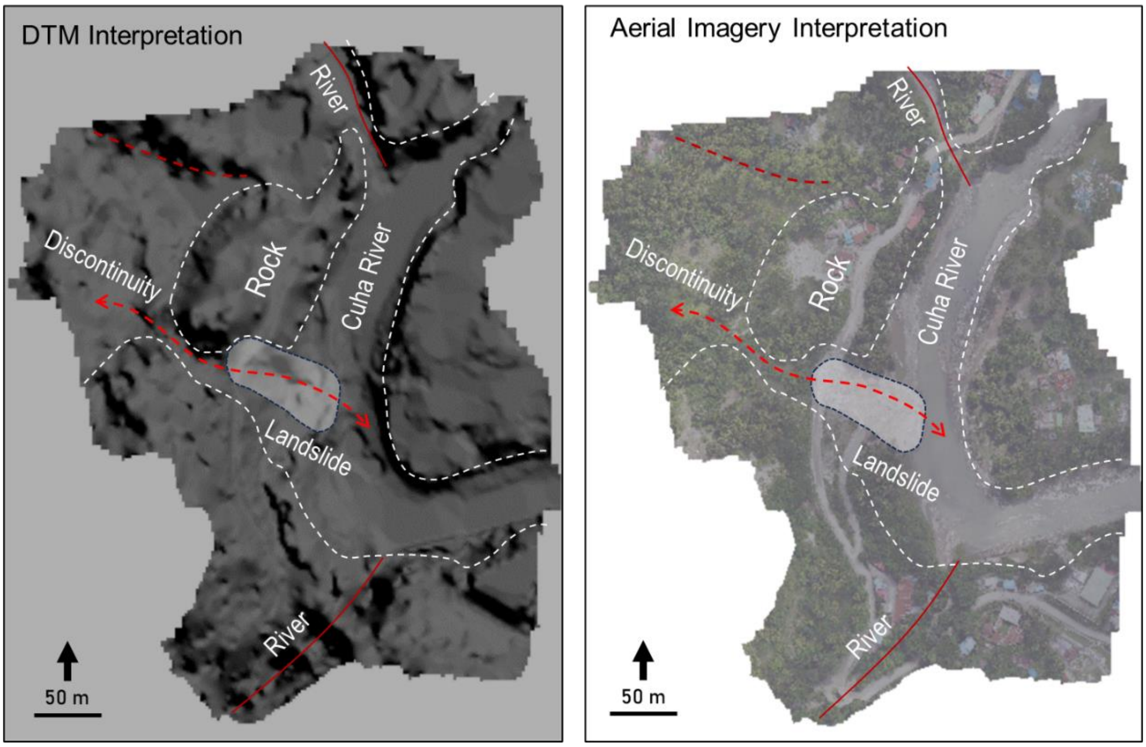

Figure 19.Interpreted drone survey

According to the DTM the surface of study showed four prominent small valley or a discontinuity shape except the Cuha River (see Figure 19). These discontinuities divided the topography into three segments in the west of Cuha River. Two of them are corresponded to the river, and two others with trend northeast-southwest are located on the high elevation that may reflect the structures. In this study the main focus a prominent discontinuity in the middle of study area with trending to the northwest-southeast. This topography feature shows an obvious shape that could occupied by soft rock that triggering road failure. Interpretation of DTM and aerial imagery are aligned to a structure suggest by Duffy *et al* (2013).

Therefore, detailed inspection along the discontinuities zone may help in identifying the structures which governed the features. To achieve this, we used geological compass to measure the direction of structures occurred on the rock. Due to the thick soil and river sediments the structure on the rock is obscure.

5.2. Geological Survey

Tectonic event in the past produced various rock deformation such as faulting, folding, and jointing well exposed in around of landslide. Geologist has well understood on the process and characteristic of the rock deformation that may contributes the valuable insight to civil engineering (Harrison and Cosgrove, 2021). Geological map with of Duffy *et al* (2013) was used. However, this broad scale does not provide a specific area a road damage in Lugatoi road failure. Limitation of available data in published geological map due to the scale does not allow to get more information for geotechnical purpose.

Figure 20.Rock and clay observed along the landslide zone

For instance, the boundary of rock unit, actual topography, and structural geology. Therefore, detail geological site observation was conducted to generate a detail geological model. This site inspection collected spatial distribution of rocks unit, structural geology, the topography, groundwater seepages, and surface water drainage. Prior conduct this information in the field, drone mapping was carried out. This drone mapping resulted orthophoto and DTM (digital terrain model). Following, observation of outcrop to delineated the boundary of rock unit and existing structural geology in the site and surrounding area. This initial geological model is essential prior to further ground investigation (Geotechnical Office Honkong, 2007).

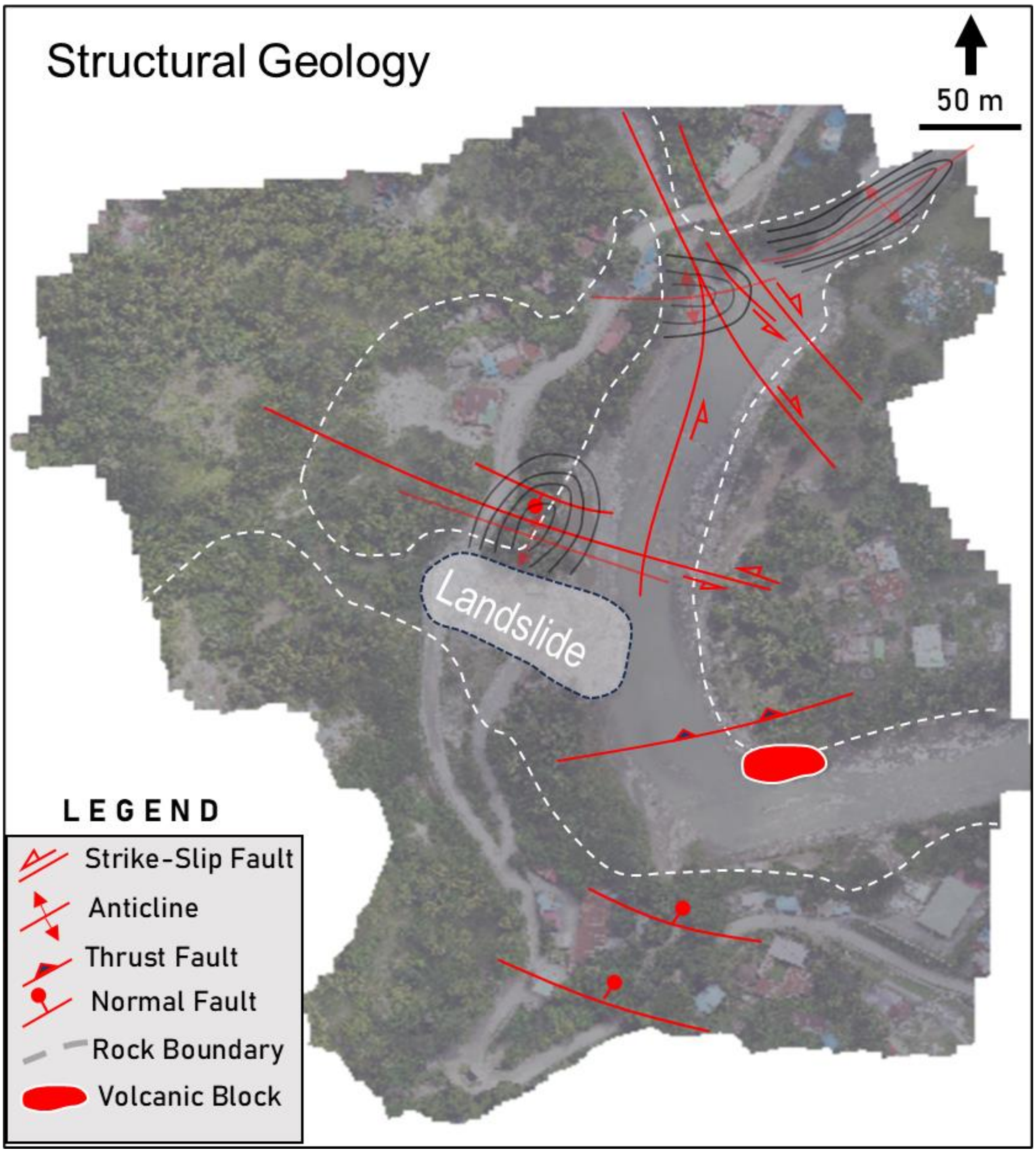

Figure 21.Structural geology overlay on aerial imagery

Litologically, two three major types of lithologies were identified such as bedding of siliceous argillite called Noni Formation, sand stone interbedded with clay called Viqueque Formation, and clay material contain oldest fragment and block called diapiric mélange material (see Figure 20). The siliceous argillite well observed in the highland, along west of Cuha River. To the south, the bedding Batu Putih formation observed along the two side or river and extended down to the Cuha River (see Figure 8). The contact of

Noni Formation and Batu Formation is obscure due to the thick soil and vegetation cover. Further to the western bank of Cuha River found fresh out crop of siliceous argillite interbedded with layer of mudstone (see Figure 22). Precisely, in the eastern bank east of landslide observed high deformed siliceous argillite that contains various fragment of rocks (see Figure 25). This can be seeing a huge block volcanic rock is located in boundary between Batu Putih and Noni formation in the south of this zone (see Figure 9). This study found that emergence dominant clay unit mix with other rock fragment related to the diapiric mélange. Where, in collision zone like Timor Island diapiric mélange is a common geology event. This finding is agreeable to the Butakoff (1969) suggest the piling of diapiric melange. This tectonic event still active till today, in 2022 in the Raisut area approximately 10 Km south of Lugatoi a huge amount of clay brough various fragment of rocks and gas from subsurface. This because buried structures act a main path way for overpressure clay material escaping to the surface. Boavida *et al* (2023) suggest the fragment of overthrust rock also found in the Raisut explosion.

Structurally, Noni Formation undergone heavy deformation compare to Batu Putih Formation. Noni formation suffered various faults, normal fault, thrust fault, strike slip fault, and folding (see Figure 23). Three major folding on Noni Formation measured, a symmetry anticline is located in north-east of landslide with the fold-axis northwest-southeast, two others in more north-east with the fold-axis northeast-southwest (see Figure 18). In addition, Batu Putih formation undergone tilting and numerous of normal fault that has relationship to rotational fault (see Figure 23). According to the drone mapping, an obvious discontinuity dismembered Noni Formation with direction northwest-southeast. Duffy *et al* (2013) depicted this feature as a fault. Filed observation found that, left-strike slip fault parallel to this structure that cut a symmetry anticline formed on Noni Formation as display in Figure 21. Moreover, the shale smear structure related to the normal fault also observed in the limb of anticline as demonstrates in Figure 22. This could interpret that a left-strike slip fault overprinted on Noni formation as the main path way for overpressure material escaping to the surface. Therefore, the fault zone mostly covered by the material of diapiric mélange zone. Further to the north-east, two others folding overprinted by multiple strike-slip fault. This coincides the small river in the north-east of landslide (see Figure 21).

Figure 22.Shale smear in a normal fault

Figure 23.Thrust fault observed on siliceous argillite (left), Rieder shear shows left strike slip fault on siliceous argillite (right)

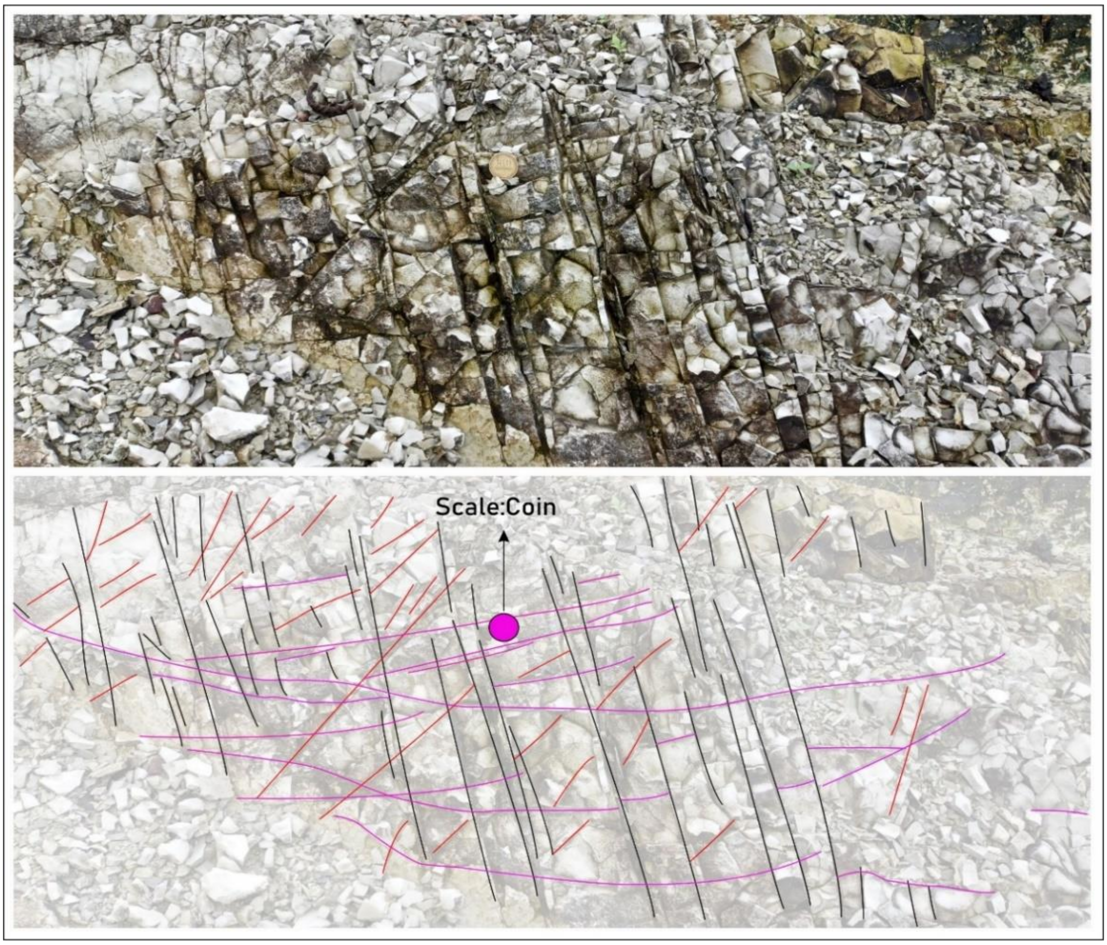

Figure 24.Joint system on siliceous argillite

Figure 25.Mudstone undergone high deformation and various block were embedded into the mudstone.

Figure 26.Rotational fault occurred on Batu Putih formation

Besides major faults, the Noni Formation undergone multiple joints. According to the field observation, in the highland a joint system comprising of four joint set as display in Figure 24. Further to the, bank of river the joints mostly parallel to the major fault. In other hand, along the joints found kaolin rich-zone (see Figure 27). The existing joints has vital influence to level of rock weathering. In the highland, both left and right side of landslide the weathering is high compare to the outcrops along the bank of river. Possible this because of exogenic role has major influence.

These geological structures allowing water infiltration into rock, presence of water considerably influences the geotechnical slope stability Therefore, identifying distribution of fault is crucial due to rock water weakening effect prone to unstable slope during high rainfall. Noni formation itself rich of clay particle where water has a greater influence on the rock. Increasing of water infiltration into fault and easily expands and disintegrates after being saturated with water.

Figure 27.Kaolin rich zone formed along the joint on siliceous argillite

One geologic event that has major factor of road damage is mud diapiric. The road damage is situated precisely on the slope of elevation that mostly covered by the clay which is the product of mud diapiric. These conditions together cause the significant slope failure during in high rainfall season. Engineering geology involvement in the early stage of feasibility study is essential due to it useful in assessing the potential hazard that may influenced the sustainability of any construction (Eddleston *et al*, 1995).

From various combination of data 3D model view was developed as display in Figure 28. This 3D view from southeast-northwest. In the left and right side of model observed Noni Formation which has opposite dip direction. In the right side observed two folding on Noni Formation with fold axis to the northwest-southeast. Numerous offsets were observed along the folding, the offset indicates left and right-strike slip fault parallel to the fold axis of folds. Further to the left side the siliceous argillite has steep dipping. This area mostly undergone high level of weathering. Joint set observed easily along the surface of outcrop. In between two Noni Formation mostly covered by the clay particle. This clay particle interpreted as the product of diapiric melange. This fascinating geological process were unconsolidated mud or shale, often under high pressure in convergent plate boundaries. The thickness of this mud diapiric believed up to hundred meters below the surface. Therefore, mud diapirs can pose hazards to infrastructure due to their potential to cause ground deformation and instability.

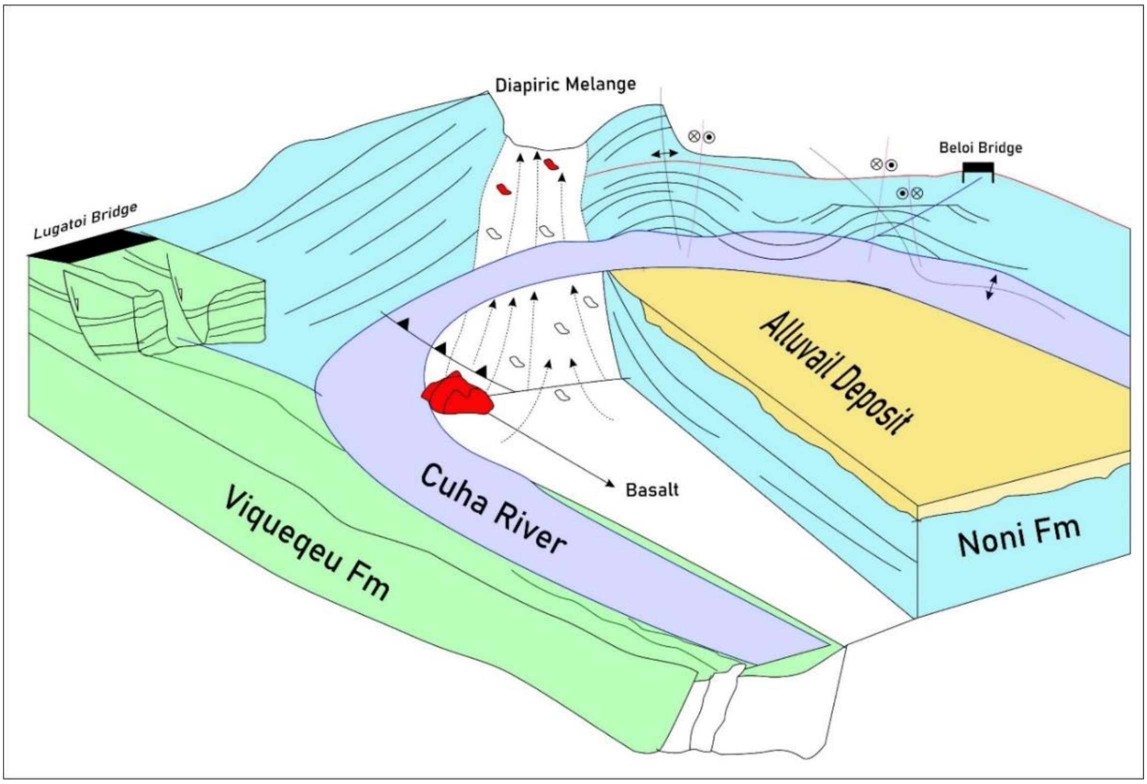

Figure 28.3D geological map view from south

5.3. Geohazard Identification

According to the geological investigation shows the landslide occurred on the area mostly covered by the clay which is product of diapiric melange. Where, structurally, the strike-slip fault governs the escaping of high-pressure material to the surface. This diapiric melange zone is challenging for road construction due to this geological formation characterized by chaotic mixture of different rocks types. Commonly, its poses clay or mud dominated. Heterogeneous composition makes its difficult in predicting the behaviour of materials. Where, varying rock types have varying strength that can lead to differential settlement. Moreover, the melange results weak and unstable material, such as various block of hard rock embedded into clay or mud. This condition has lack cohesion and are prone to deformation and movement under stress. Besides that, the diapiric melange zones are frequently associated with groundwater seepages issues. Over time this water increases the pore water pressure as consequence reduces the friction between soil particles and reduce the load bearing capacity of materials. This condition makes the material more susceptible that can lead slope movement and failure. Furthermore, diapiric melange involves complex geological process that can result various faults, discontinuity of rocks, and other structural features which is may compromise the stability of road foundation.

Figure 29.Natural Spring emerge in the landslide (left), poor surface drainage in the highland (right)

Poor drainage around the diapiric zone is one of the most issue was observed. Infiltration of surface through the open crack in the highest elevation flowing underneath of subsurface then emerge on the surface (natural spring) in the location of slope failure (see Figure 29).

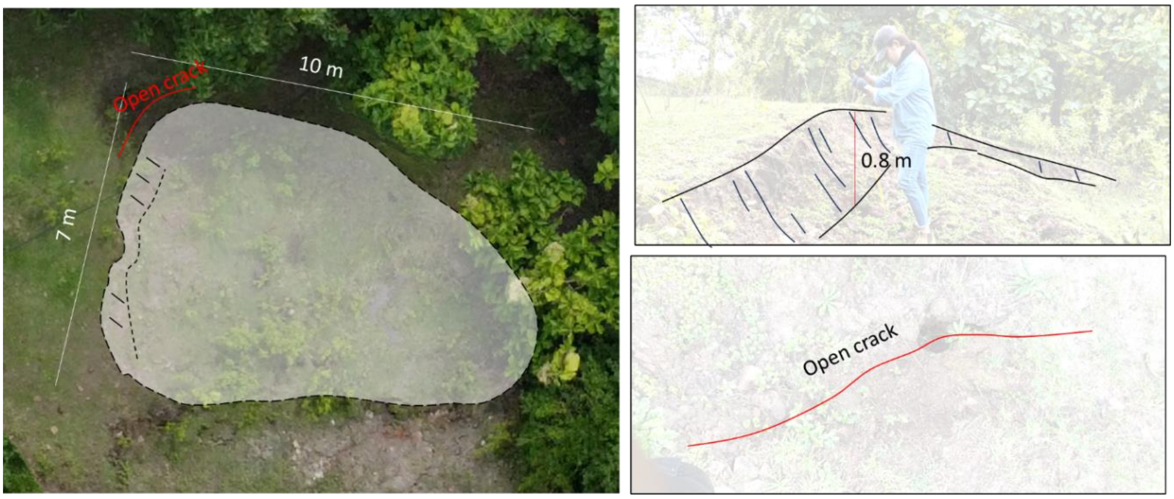

Figure 30.Obvious landslide in the highland.

The observation concluded that the has high plasticity and this exhibit significant volume changes with variations in moisture content. This volume change over time is the main cause that led to landslide which is demolishing the road in Lugatoi area. A small rotational landslide observed with length 10 m and width 7 m. The main scarp moved down around 0.8 m (see Figure 30).

Figure 31.Cracking and plasticity test in field

Obsrvation in field indicates shrink-swell behaviour where the dry clay has cracking this relates to losse of moisture cause it to shrink. Moreover, clay testing field shows the clay flowing oput in bertween the fingers when squezeed. This mean the clay has high plasticity (see Figure 31).

5.4. Geophysics Survey

Six VES points used Schlumberger protocol were measured. Three VES points were located linearly within the landslide, remaining points were out of landslide (see Figure 32). The graphic of inversion each point as displayed in Figure 33. The x-axis represents the AB/2 value while the y-axis representing the resistivity value of subsurface material.

Varying of electrodes spacing allows obtain the information at different depths. Variations of subsurface resistivity values may help in distinguishing the geological layers and their properties. As display in Figure 33, each VES point undergone gradual to steep decreasing resistivity values. Fluctuation of observed and obtained model in each graphic reflect the different lithologies and their properties beneath the surface of study area. Moreover, different lithologies and properties could use to predict the water table and candidate failure surface.

VES profile useful in determining the sequence of rock or soil strata based on variations in material resistivity values. Table 1 demonstrate the information that obtain from the VES graphic in Figure 33.

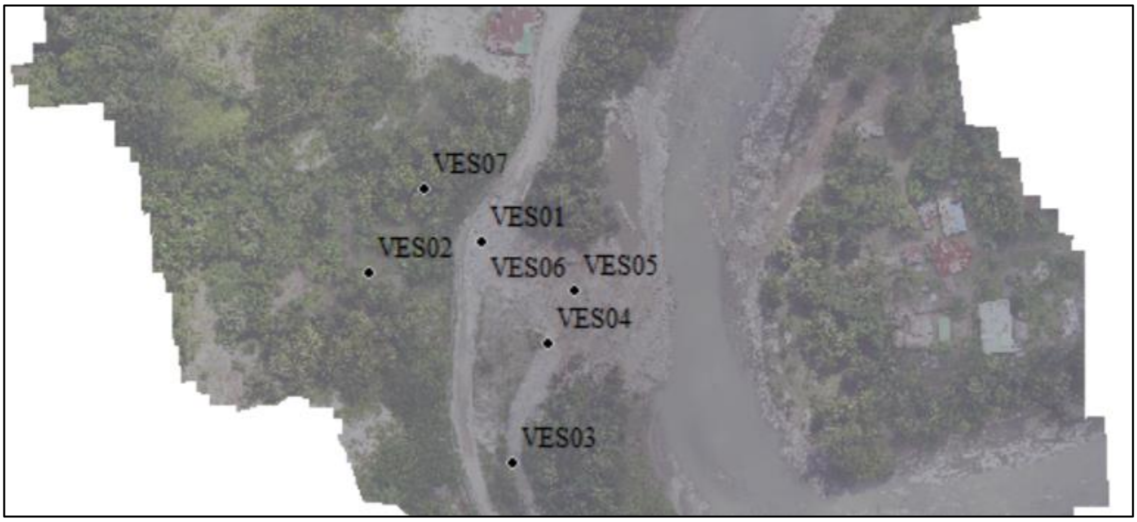

Figure 32.Location of VES point

The graphics contain detail information in characterizing the subsurface condition, which is subsurface layers including thickness, composition and continuity. Overall, the VES data show the top layers are high at surface up to 0.5 to 1 m. Down to this depth the resistivity value decrease reflects the different composition of materials.

According to the space, allowing the penetration depth of VES line varies from 20 m to 30 m. Obtained resistivity value are ranged from 1 ohm-m to 273 ohm-m. The highest value interpreted as the volcanic material that embedded into the clay. While middle to lowest value reflected to wet clay and very wet clay. Decreasing of value due to the increasing moisture content in soil, and this often has strong relationship to the higher percentage of fine clay particle. In other hand quantity of water in clay has significant effect on resistivity value. In addition, particle size distribution of clay determines the degree of water saturation. (Kalinski & Kelly, 1993) revealed that increasing of water conductivity that occupied in pores space reducing the resistivity value. The very wet clay of each point is observed at depth 0.5 m to 6 m. Presence of very wet clay layers are well agreeable to the emergence of natural spring along the landslide zone. This because unwell surface water treatment in highland of landslide zone.

In Figure 34, profile of VES data was built according to the Table 1. The models display variations of resistivity value beneath the surface. Averall, the VES01 and VES02 show different material in the top layer, where the increasing of resistivity value due to the infill material of sand gravel and volcanic material respectively.

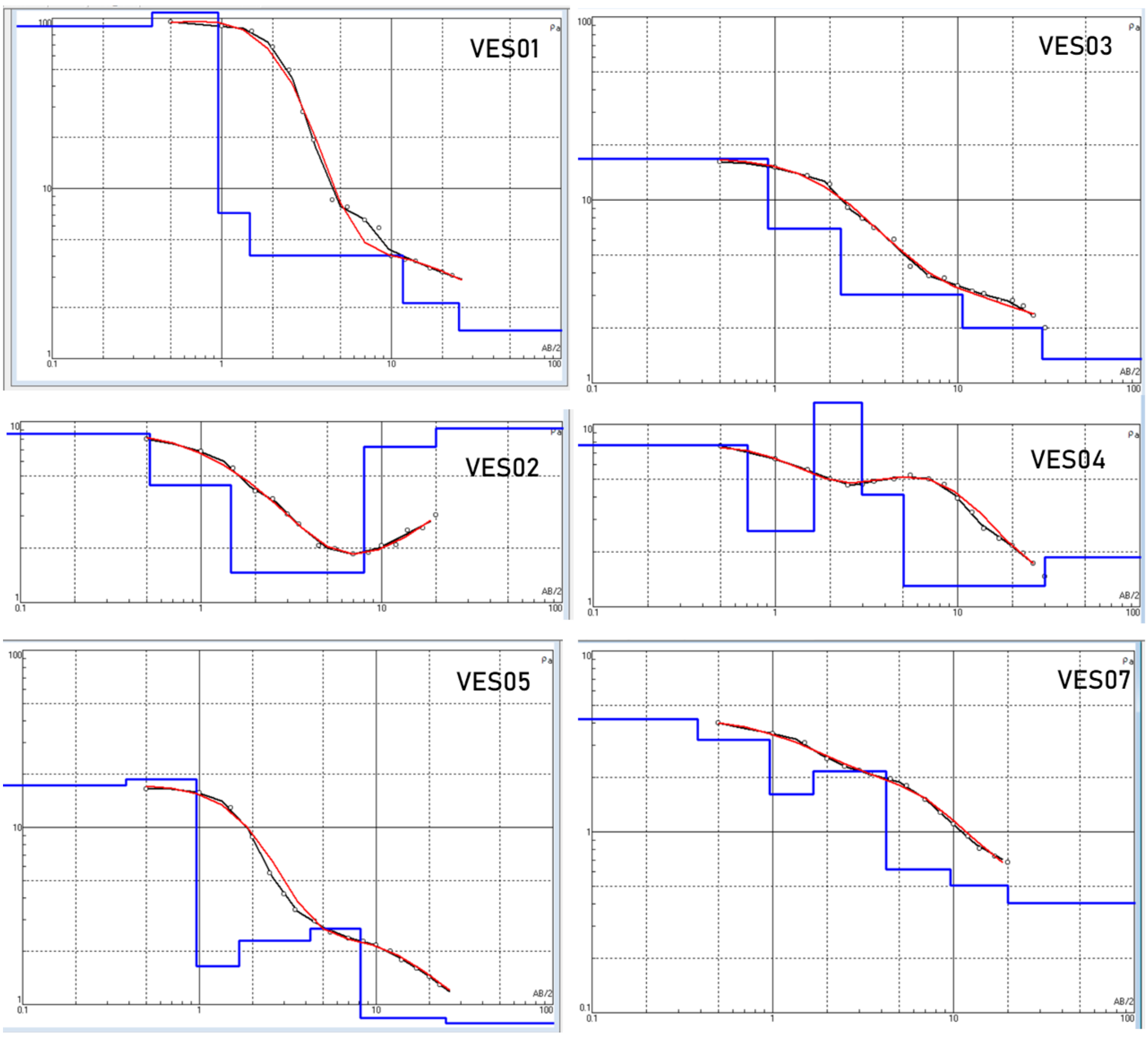

Figure 33.Inversion of VES data

The surface condition can see in Figure 10. The thickness of these material around 0.5 in in VES01 and 0.98 in VES02. Up to this depth (around depth 20-25 m) found lowest resistivity that reflected the piling diapiric mélange. The VES03, VES04, and VES05 are located in the excavated zone, the surface was compacted for road access. The compaction layers well defined in resistivity profile with depth around 0.7 m to 0.9m. The subsequent layer is very wet clay material with depth 25 m – 30 m. Finally, the VES07 is located in highland around 20 m from main scarp of landslide that demolishing the road. The top layer is moist soil with thickness 0.38 m, following very wet clay as the product diapiric mélange could reach to depth 20 m. The very wet clay layer interprets the product of diapiric material which is very rare mix with block alien rock causes low values of resistivity.

Table 1.*Interpretation of VES data*

VES	Depth (m)	Resistivity (Ωm)	Lithology	Interpretation
VES-1	0 – 0.38	89.8	Sand and gravel	Infill material
	0.38- 0.98	145	Gravel	Infill material
	0.98 – 1.43	7.2	Wet clay	Diapiric material
	1.43– 11.7	4.04	Very wet clay	Diapiric material
	11.7 -25	2.12	Very wet clay	Diapiric material
	25 - ?	1.46	Very wet clay	Diapiric material
VES-2	0 – 0.51	8.57	Soil and volcanic fragment	Diapiric material
	0.51 – 1.46	4.45	Wet clay	Diapiric material
	1.46 – 7.99	1.46	Very wet clay	Diapiric material
	7.99-20	7.25	Wet clay	Diapiric material
	20 -?	9.16	Wet clay	Diapiric material
VES-3	0 – 0.9 1	16.8	Dry Consolidated material	Infill material
	0.91 – 2.29	7	Wet consolidated material	Infill material
	2.29 – 10.6	3	Very wet clay	Diapiric material
	10.6 - 30	2	Very wet clay	Diapiric material
	30 - ?	1.35	Very wet clay	Diapiric material
VES-4	0 -0.7	7.7	Consolidated material	Infill material
	0.7 – 1.63	2.61	Very wet clay	Diapiric material
	1.63 – 2.99	13.2	Dry clay	Diapiric material
	2.99 – 5.05	4.12	Very wet clay	Diapiric material
	5.05 – 30	1.3	Very wet clay	Diapiric material
	30 - ?	1.8	Very wet clay	Diapiric material
VES-5	0 – 0.38	14.9	Consolidated material	Infill material
	0.38 – 0.96	18.7	Very consolidated material	Infill material
	0.96 – 1.67	1.65	Very wet clay	Diapiric material
	1.67– 4.24	2.3	Very wet clay	Diapiric material
	4.24 – 8.15	2.68	Very wet clay	Diapiric material
	8.15-25	0.83	Very wet clay	Diapiric material
	25 - ?	0.71	Very wet clay	Diapiric material
VES-7	0 – 0.38	4.2	Very wet soil	Soil material
	0.38 – 0.96	3.22	Very wet clay	Diapiric material
	0.96 – 1.67	1.61	Very wet clay	Diapiric material
	1.67 – 4.23	2.16	Very wet clay	Diapiric material
	4.23 – 9.6	0.62	Very wet clay	Diapiric material
	9.62 - 20	0.50	Very wet clay	Diapiric material
	20 - ?	0.40	Very wet clay	Diapiric material

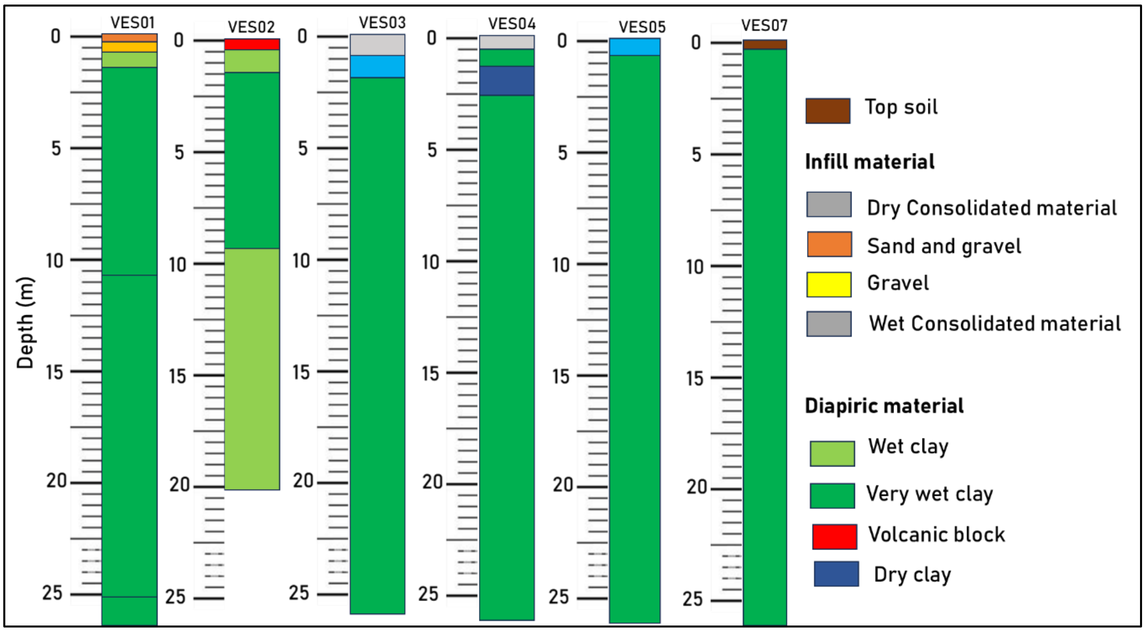

Figure 34.VES profile in study area

In this study the VES model well reveal the variations of resistivity values the useful in determining the degree of saturation below the road failure and surrounding area. This could allow us in characterizing the landslide due increasing of water saturation reduce the internal cohesion of soil (Crawford and Bryson, 2018). Moreover, resistivity values depend on the degree of compaction, water content, degree of saturation, porosity, and clay content, all of which are strongly related to geotechnical purposes. Furthermore, the VES data could guide the engineer to locate the borehole, and may helping in eliminating less favorable alternative sites.

According to various data a subsurface profile was developed in Figure 35. The profile created from VES-07 in highland and VES-05 in bank of Cuha River. Along the landslide zone found numerous natural springs. Mosty the landslide occupied by very fine particle of clay. The top layer of profile considering as the dry clay, up to depth 0.5 m decreasing of resistivity value interpreted as very wet clay layer. This interpretation support by the distribution of natural spiring occurred along landslide zone. The model is agreeable to the geological observation. The excavation exposed the thickness of clay material of diapiric mélange observed from the bank river up to the highland along the strike slip fault.

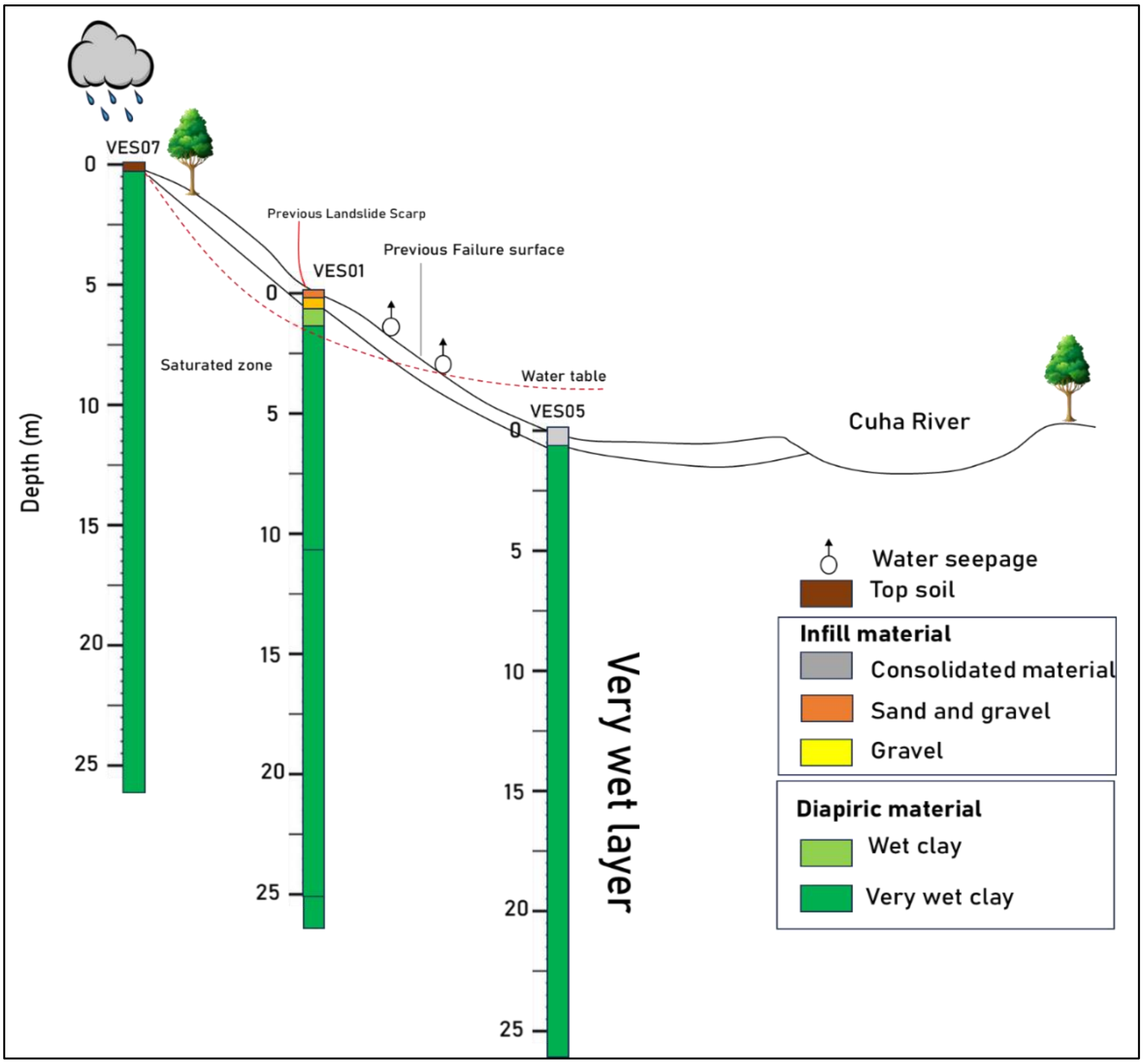

Figure 35.Subsurface profile cross over the landslide zone

5.5. Geotech Investigation

In this survey, four sample for mechanical and physical test were collected. The location of sample collection as display in Figure 36. In particularly, the shear strength analysis applied only for three samples (BH1, BH2, BH3) due one sample (BH4) was collected by heavy machine of company was constructing the road maintenance (piling method). Prior to collecting sample, defining sample location that representative of the soil conditions based on geological information. BH1 was collected in the highland beyond the landslide zone. BH2 and BH4 were collected in the landslide zone. BH3 collected on a weathered outcrop of siliceous argillite in left-side of landslide (see Figure 36 and 37). For BH1, BH2 and BH3 sampled disturbed sample using hand auger. While, undisturbed sample tubes to preserve original soil structure. Samples of BH1, BH2, and BH3 collected on origin material with a depth 50 cm. BH4 sampled at depth 6 m. The physical character of samples as illustrates in Figure 37.

Figure 36. Location Geotech samples.

According to test in the field using finger to very wet clay samples (BH1 and BH2), both samples have high plasticity due to it flowing in between fingers. This because of increasing of water into the surface and poor surface water treatment. Increasing of plasticity indicates abundance of clay material. This wet clay tends to be weaker due to its reduced shear strength and increased plasticity, posing challenges for foundation stability.

The soil swelling high influenced by three ingredients that could demolished the structures such as; high content of clay, natural water in plastic limit of soil, and source of water for potentially swealing soil (Holts and Kovacs, 1981). Various researcher (Kalantari, 1991, Murphy, 2010, Coduto *et al*, 2010) state that the swelling could occur at depth 1-20 m, it depends on the location for instance in an unstable zone. According to the observation shows road damage at Lugatoi is precisely located on the area which mostly covered by the high plasticity clay. Recent excavation along the landslide zone exhibits the same clay material observed at the bank or river continue up to main scarp of landslide (its thickness around 20 m). The observation is equal to the VES resistivity data where from 0.5 to 25-30 m depth mostly occupied by very wet clay material.

Figure 37.Character of soil and rock samples

Laboratory analysis shows the clay of diapiric material and siliceous argillite have high moisture content (see Table 2). The clay material is ranged from 31.59 % to 99.39 %, while the siliceous argillite is 48.15%. According to MMD (2007) the moisture content value up to 30% classified as very wet material. In this study, the lowest value of moisture content is 31.59%. This condition affects the bearing capacity and stability of road at Lugatio due to high moisture content can lead to softening underground material, which may compromise foundation integrity.

The liquid limit reflects the water content at which soil change from a plastic state to a liquid state. This parameter is a critical parameter in geotechnical engineering. Where, material with high liquid limit is more prone to deformation due to it may reduce the bearing capacity that led to road failure. From the result of the study the liquid limit of clay material obtained range from 64.30% to 105.97% (see Table 3).

Table 2.*Moisture content of samples*

Samples	Moisture Content (%)	Classification
BH01	99.39	Saturated clay
BH02	72.81	Saturated clay
BH03	48.15	Saturated Siliceous argillite
BH04	31.59	Wet clay

The siliceous argillite in BH03 has value 83.96%. Snethen (1977) states that the liquid limit of material up to 60% classified as very high liquid limit. Following, Chen (1965) considering this highest value categorized as the very high in swell potential. This high liquid limit of material believed as the main control of road failure at Lugatoi. During high rainfall, poor surface drainage induces amount of water into subsurface. Increasing of water content reducing the bearing capacity, making them unsuitable for supporting the heavy loas road on a high slope.

Table 3.*Liquid limit and expansive classification*

Samples	Liquid Limit (%)	Swell Potential (Chen 1965)
BH01	105.97	Very High
BH02	64.30	Very High
BH03	83.96	Very High
BH04	106.23	Very High

Plasticity index is calculated by subtracting the plastic limit from liquid limit of material. This parameter useful in understanding the material behavior under varying moisture condition. Increasing of plasticity index indicates the material has high content of clay which is has significant volume change with moisture variations. Table 4 present plasticity index value in this study, where found the plasticity index ranged from 18.30% to 87.9%. The clay material of diapiric has lowest value (18.30%) compare to siliceous argillite (27.29%). According to Chen (1988) the plasticity index value up to 18% reflects medium value, and the value up to 25% is high plasticity. Following Holtz and Gibbs (1956) classified the highest plasticity value has high potential of material swelling. This high plasticity governed the volume change of material, when the material absorbs the water, they expand, and they shrink when dry out. This well observed on original outcrop in the field, the clay material crack after it release water (see

Figure 31). Poor surface drainage enhances water content, which can weaken the road base. The repeated overtime can cause a landslide in a unstable slope as Lugatoi area.

Table 4*.Plasticity index and expansive classification*

Samples	Plasticity Index (%)	Swell Potential (Holtz and Gibbs 1956)
BH01	77.4	High
BH02	18.30	High
BH03	27.29	High
BH04	87.9	High

Following, the value of the direct shear test has been identified and listed in the table below.

Table 5*.Soil Parameter test*

Nu.	Soil Parameter	Unit	BH-1	BH-2	BH-3
1	Unit Weight (γ)	kN/m^3	15.460	15.360	15.310
2	Cohesion (c)	kN/m^2	1.032	-26.209	0.619
3	Friction Angle (ϕ)	...°	3.860	49.690	8.790

This is caused by the shifting of rock or soil masses with various types and types such as falling rocks or large lumps of soil. Landslides are closely related to slope gradients. Landslides can cause very large losses and impacts, including material losses in the form of houses, roads, public facilities, and agricultural land.

The safety factor value for the possibility of slope landslides and slope design according to Bowles, J. E. can be seen in the table. 6.

Table 6. *Relationship between Safety Factor values and the possibility of landslides on slope area (Das B M, 1993).*

SF Value	Slope Condition
< 1,07	Unstable
1,07 < SF < 1,25	Critical
> 1,25	Relatively Stable

By using the Hyrcan application ver. 2.0, it is shown the value of the Safety Factor (SF) of the slope with the Simplified Bishop method has a value 0,461. Thus, it can be stated that the slope is unstable and already still in failure condition.

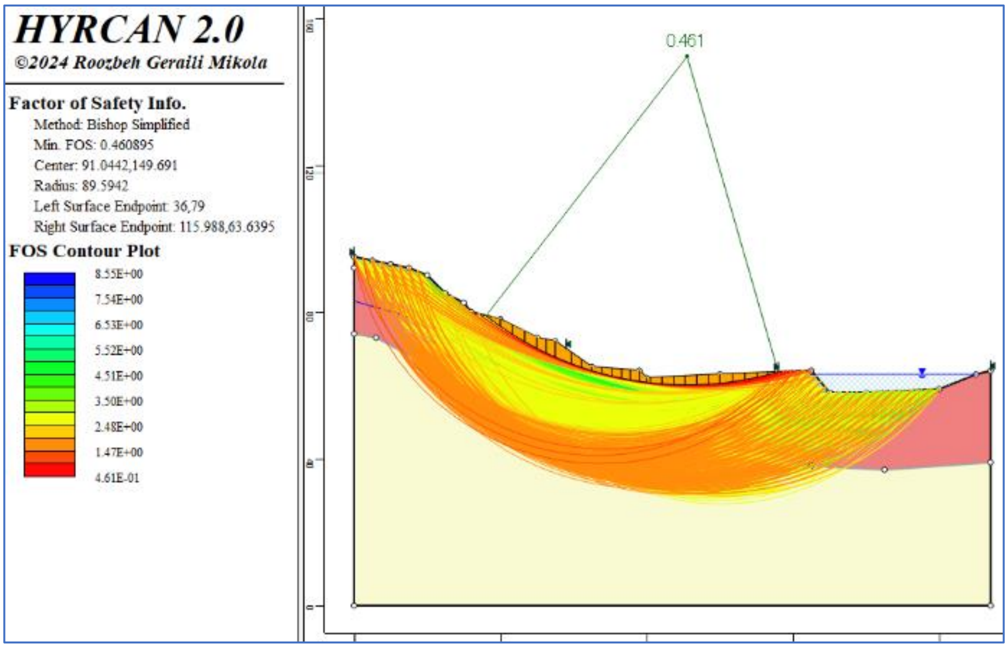

Figure 38.The slope stability analysis during Failure Condition

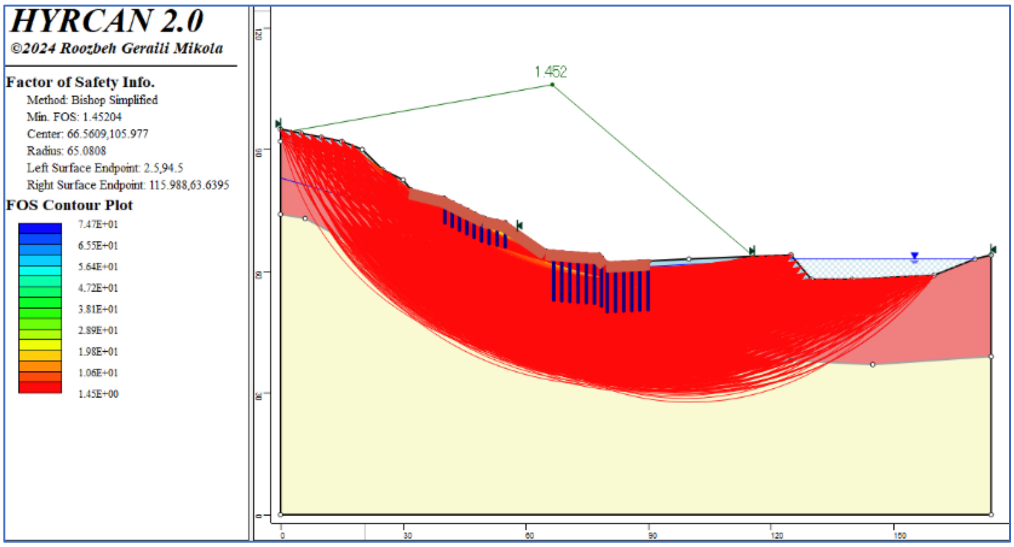

Figure 39.The slope stability analysis after reinforcing with combination of bored pile and gabions.

Given the substandard slope conditions and the consequent low safety factor value of 0.461, the proposed solution is to reinforce the area using a combination of bored pile foundations and soil retention techniques, including the use of gabions.

By using the Hyrcan application ver. 2.0, it is shown the value of the Safety Factor (SF) of the slope with the Simplified Bishop method has a value 1,452. Thus, it can be stated that the slope is stable or safe after reinforced by combination of pilling and gabions.

Table 7.*Design of Bored pile foundation retaining wall*

Nu.	Soil Parameter	Notation	Value	Unit
1	On bored pile foundation	DM/B	0,50	m
2	Bored pile foundation depth	DM/B	12	m
3	Pile group length	L	30	m
4	Concrete quality	-	20,75	MPa
5	Stell quality	-	300	MPa

Source: Calculation results

Drawing type model for slope reinforcement using combination of bored pile and gabions.

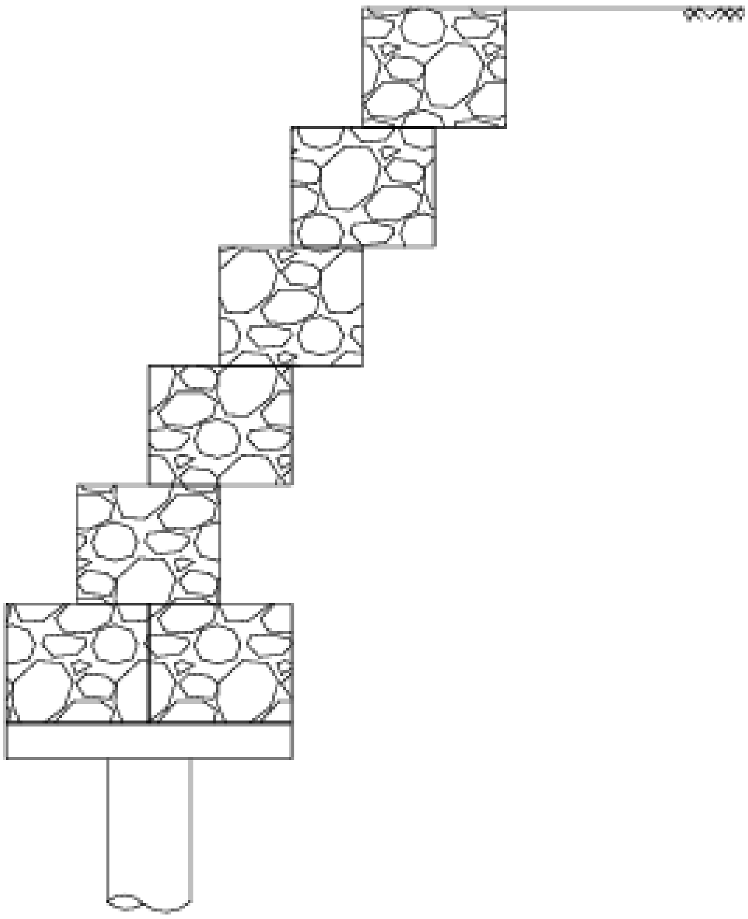

Figure 40.Retaining wall plans

6. DATA CORRELATION

Combination of Geotech information, geology and geophysical data are essential in order to obtain high resolution of result. Integration of data shows ddiapiric melange occurrence strongly related to the strike-slip fault with trend northwest-southeast. This support by the VES data, where the study area has thick diapiric mélange material, possible up to the depth 30 m. From depth 0.5 the resistivity values decrease correspond to the very wet clay. Poor surface water drainage allows water infiltration into the subsurface. Where, high saturated play important role of road damage in Lugatoi because water is the main key controlling the slope stability

Table 8*. Integration of all data in this study*

No.	VES	Geology	Geotech	Drone	Interpretation
1	**VES02** Up to 0.5 is low resistivity.	Dominant clay, volcanic rock, strike-slip fault.	BH01 High moisture content, plasticity, and liquid limit	Discontinuity, valley	Fault zone, occupied by diapiric material
2	**VES01** Infill material thickness is 1 m, up to this depth is low resistivity.	Dominant clay exposed due to excavation. Numerous natural seeps occurred on surface.	**BH 2** High moisture content, plasticity, and liquid limit	Discontinuity, valley	Fault zone, occupied by diapiric material
3	VES03 Compact Infill material thickness is 1 m, up to this depth is low resistivity.	Excavation exposed the weather siliceous argillite along the cliff.	-	Clif (Excavation)	Excavated zone, to the deeper depth is diapiric material.
4	VES04 Compact Infill material thickness is 0.7 m, up to this depth is low resistivity.	Excavation exposed the weather siliceous argillite along the cliff.	BH3 High moisture content, plasticity, and liquid limit	Cliff (excavation)	Excavated zone, to the deeper depth is diapiric material.
5	VES05 Compact Infill material thickness is 1 m, up to this depth is low resistivity.	Excavation exposed clay material, product of diapiric melange	BH-4 High moisture content, plasticity, and liquid limit	Excavation in landslide	Fault zone, occupied by diapiric material
6	VES07 Wet soil thickness is 0.3 m, up to this depth is low resistivity.	A valley covered by soil.	-	Discontinuity, valley	Fault zone, occupied by diapiric material

Overtime the water pressure increase as consequence decreasing in internal material cohesion and enhancing the material plasticity. Samples analysis is aligned to the field investigation. For instance, clay material of diapiric mélange has high plasticity and low shear strength compare to siliceous argillite. This caused the slope failure that demolish the road frequently. The geotechnical model reveals the safety factor is around 0.46. Therefore, without proper analysis not guarantee longevity of road maintenance. Various maintenance method has been applied in the last 3 to 4 years. Unfortunately, lack of deep investigation during planning and construction phases of road maintenance led to frequent failures. This often-costly repairs, delays, and even complete project overruns.

The ongoing road failure maintenance construction using the piling method with depth 6 m in the toe of landslide and 12 m depth in the middle of landslide (see Figure 41), the blue box is the location of piling. Nevertheless, the piling concentrates in landslide only, not extended further to the left and right flank of landslide that occupied by siliceous argillite of Noni Formation. This is dangerous due to the ongoing surface movement on the left flank of the landslide. The gabion shows significant movement on the surface (Figure 41D). Further up the highland, a few meters from the main scarp of the recent landslide, an actual landslide occurred with a length of around 10 meters. Moreover, the pistol-shaped coconut tree is a possible indication of creeping.

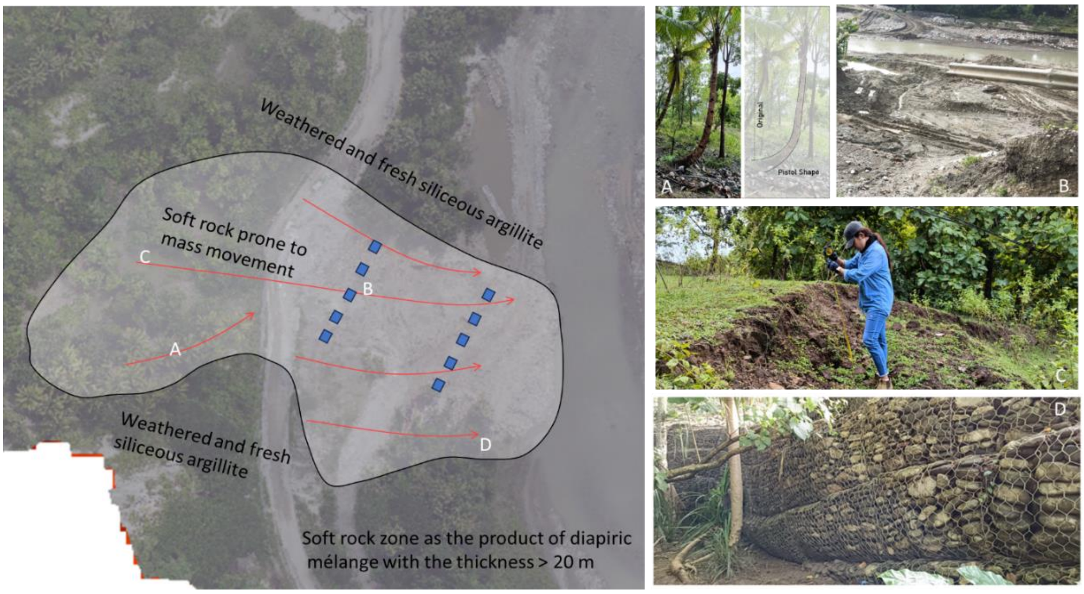

Figure 41.Potential landslide map and indication in field.

According to our analysis, we recommended pile foundation and retaining wall. The method result the safety of factor increase to 1.452. In order to guarantee the longevity of road maintenance the piling should extend to the hard rock in left and right flank of landslide. Furthermore, surface water pattern treatment to avoid infiltration of water into subsurface. Move the new road to hard rock that has risk in landslide and avoiding steep slopes that formed by the clay that prone to landslide. Furthermore, manage the water flow pattern to minimize water-related issues.

7. CONCLUSSION

According to preliminary interpretation come to conclusion as follows:

1. Drone mapping reveal a discontinuity morphology are agreeable to geological strike-slip geological structures parallel to landslide and discontinuity zone. The road failure is located on an unstable slope (around 45-0 degree)
2. Geological condition (diapiric mélange material) as the main issue of landslide, in addition poor surface water treatment accelerate the landslide. In addition, multiple joint set on siliceous argillite governed the level of weathering.
3. VES data reveal the very wet zone of clay material found at depth 0.5 m up to 30 m.
4. Clay material and siliceous argillite have high moisture content, liquid, plasticity index, and direct shear.

8. RECOMMENDATION

According to the result of investigation we recommended:

1. Further 2D resistivity to understand the subsurface distribution of hard rock of siliceous argillite in left-flank landslide.
2. The 2D resistivity model may help in defining the location piling due to the piling should extent to hard rock.
3. Piling method and gabion are proposed, but surface water treatment need to improve to enhance the longevity of methods.
4. Alternative road at low slope elevation following the bank of river that has hard rock.

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